

Analysis of High-Frequency Broadband Acoustic Scattering from Non-Linear Internal Waves during SW06

Andone C. Lavery

Department of Applied Ocean Physics and Engineering

Woods Hole Oceanographic Institution

Bigelow 211, MS #11, Woods Hole, MA 02543

telephone: (508) 289-2345 fax: (508) 457-2194 email: alavery@whoi.edu

Award Number: N00014-02-10359

LONG-TERM GOALS

To understand high-frequency broadband acoustic backscattering from small-scale physical processes, such as internal waves, turbulence, and microstructure, in shallow, stratified coastal waters.

OBJECTIVES

The primary objective of the proposed research was to measure high-frequency broadband acoustic backscattering in highly stratified, energetic environments and to determine the contribution to scattering from temperature and salinity microstructure. Testing the validity of existing scattering models and the initial development of new, and/or extension of existing, simple physics-based scattering models was a secondary objective of this work.

To accomplish the stated objectives, high-frequency broadband (150-600 kHz) acoustic backscattering measurements were performed during the generation, propagation, and dissipation of non-linear internal waves in August 2006 as a part of the SW06/NLIWI experiment. Almost coincident microstructure measurements were collected by Jim Moum with a profiling microstructure instrument, Chameleon. The contribution to scattering from biological organisms was quantified using a multiple-opening and closing net and environmental sensing system (MOCNESS), from which the zooplankton taxa, size, and depth (in coarse vertical bins) can be determined. The particular effort described here focuses on the analysis on these data.

APPROACH

Over the last 40 years, there has been significant research effort directed at using high-frequency acoustic scattering techniques to remotely investigate the distribution, abundance, and size of marine organisms (Simmonds and MacLennan, 2005, and references therein). In fact, some of the world's largest stocks of zooplankton, such as Antarctic Krill (Nicol and Endo, 1999), as well as large fish stocks, are assessed using single or multi-frequency narrowband acoustic scattering techniques (Simmonds and MacLennan, 2005). More recently, there has also been significant effort directed towards the quantitative use of narrowband acoustic scattering techniques for investigating small-scale physical processes, such as oceanic microstructure (e.g. Goodman, 1990; Seim et al 1995; Lavery *et al.*

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE SEP 2009		2. REPORT TYPE Annual		3. DATES COVERED 00-00-2009 to 00-00-2009	
4. TITLE AND SUBTITLE Analysis Of High-Frequency Broadband Acoustic Scattering From Non-Linear Internal Waves During SW06				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution, Department of Applied Ocean Physics and Engineering, Bigelow 211, MS #11, Woods Hole, MA, 02543				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Code 1 only					
14. ABSTRACT To understand high-frequency broadband acoustic backscattering from small-scale physical processes, such as internal waves, turbulence, and microstructure, in shallow, stratified coastal waters.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

2003; Ross and Lueck, 2003; Warren et al, 2003). Acoustic scattering techniques provide a rapid, high-resolution, synoptic, remote sensing alternative to more traditional sampling strategies. Yet reducing the ambiguities in the quantitative interpretation of the acoustic returns, with the ultimate goal of accurate, remote classification and quantification of physical and/or biological scattering sources, remains one of the outstanding challenges.

In principle, measurements of high-frequency acoustic scattering from oceanic microstructure and zooplankton across a broad range of frequencies, spanning multiple octaves of bandwidth, can reduce the ambiguities typically associated to the interpretation of acoustic scattering at a single frequency or a limited number of discrete narrowband frequencies. The goal is to capitalize on the different characteristic frequency-dependent spectra associated to different scattering sources. The potential for this technique is supported by broadband measurements on caged aggregations of fish (e.g. Simmonds and Armstrong, 1990; Simmonds *et al.*, 1996), free-swimming individual fish (e.g. Lundgren and Nielsen, 2008), and numerous broadband laboratory measurements of fish (e.g. Reeder *et al.*, 2003; Au and Benoit-Bird, 2008), squid (e.g. Lee *et al.*, 2009), zooplankton (e.g. Roberts and Jaffe, 2008), and different types of microstructure (e.g. Goodman and Oeschger, 2003; Lavery and Ross, 2007), as well as the fact that many toothed whales use broadband echolocation signals to detect and classify their prey (Au *et al.*, 1999).

There are only a few commercially available (Ross and Lawson, 2009: 85–155 kHz, slightly less than an octave bandwidth), or custom-built prototype (Foote *et al.*, 2005: 25 kHz to 3.2 MHz using seven octave bandwidth transducers), high-frequency broadband acoustic backscattering systems that have been used for studying zooplankton and/or microstructure in the field. In contrast, lower-frequency broadband acoustic scattering measurements ($< \sim 120$ kHz) to remotely characterize fish have been performed more prevalently (e.g. Zakharia et al., 1996; Stanton *et al.* accepted), including measurements involving explosives (e.g. Holliday, 1972; Thompson and Love, 1996; Nero *et al.*, 1998; Love *et al.*, 2004).

The broadband system developed for this project was used to measure high-frequency broadband acoustic backscattering from microstructure and zooplankton in the presence of surface trapped nonlinear internal waves of depression propagating over the New Jersey continental shelf. The frequency range used in this study encompasses many of the narrowband acoustic frequencies typically used to survey zooplankton and turbulent oceanic microstructure, and includes the Rayleigh-to-geometric scattering transition of some typical zooplankton and the diffusive roll-off in the spectrum for scattering from turbulent temperature microstructure for a range of dissipation rates. Almost coincident direct microstructure measurements were performed. Zooplankton community structure was characterized using depth-resolved net-sampling techniques. Some marine organisms, predominantly small fish and zooplankton, can act as passive tracers of physical processes such as internal waves and turbulence, and are a significant confounding factor during the interpretation of high-frequency acoustic volume backscattering. The combination of these data is necessary for the accurate interpretation of the acoustic scattering measurements and, in particular, to determine the relative contribution to scattering from zooplankton and turbulent microstructure. Surface trapped nonlinear internal solitary waves of depression are a unique feature of coastal oceans and provide a good environment to assess the contribution to scattering from oceanic microstructure as they are both intensely turbulent (Moum *et al.*, 2003) and at sufficiently close range that they generate high signal levels well within the range of surface-deployed, high-frequency broadband acoustic scattering systems. Surface trapped nonlinear

internal waves of depression are thought to be generated in the vicinity of the continental shelf break due to the interaction of internal tides with stratified fluid over sharp topography. They then propagate across the continental shelf until they dissipate in shallower waters. Not all the internal wave energy is dissipated in shallow waters, as some is dissipated by the generation of turbulence along the propagation path. Mechanisms for this dissipation of energy are discussed by Moum *et al.* (2003). It is hoped that quantification of broadband acoustic scattering from microstructure generated by these nonlinear internal waves may contribute to understanding these dissipation mechanisms.

The data analysis involves capitalizing on the broadband nature of the transmitted signals and using pulse compression techniques (Chu and Stanton, 1998; Stanton and Chu, 2008) to both increase the signal to noise ratio and the spatial resolution of the measurements. It has been possible to obtain almost cm scale resolution in the direction of acoustic propagation using these techniques, a significant improvement over traditional single-frequency echosounder observations of water-column scattering. Additional information is obtained by further capitalizing on the broadband nature of the acoustic signals by using the spectral content of the scattering to determine if the scattering is consistent with scattering from small-scale physical processes or biology. In regions in which the scattering is determined to be dominated by turbulent microstructure, scattering models are used to extract parameters such as the dissipation rate of turbulent kinetic energy.

WORK COMPLETED

Instrument development and calibration: A 4-channel high-frequency broadband acoustic backscattering system has been developed spanning the frequency range, in four almost overlapping bins, from 150 kHz to 590 kHz with similar acoustic scattering volumes. The system is designed to either profile with the transducers in a side-looking mode or to be suspended at a particular depth with down-looking transducers (resembling a more traditional echosounder). A SeaBird SBE 49 FastCAT CTD (16 Hz sampling rate) is mounted on the system to measure fine-scale temperature and salinity gradients while in profiling mode. Pitch, roll, and heading are also measured. GPS data are recorded to allow accurate synchronization with other instruments. The system has been calibrated, including measurements of beam patterns, in sea-water tanks at WHOI and at SMAST (on multiple occasions), in the WHOI sea well (also on multiple occasions), and in-situ, using 20 mm and 38.01 mm diameter Tungsten Carbide standard targets

Field measurements: This system has been deployed during the SW06/NLIWI experiment during a month long cruise (July 30- August 28, 2006) on the RV Oceanus. Direct microstructure measurements were performed by Jim Moum using the turbulence profiler Chameleon (Moum *et al.*, 1995). The broadband acoustic system was fully operational throughout the experiment and high-frequency broadband acoustic backscattering has been measured for 28 internal solitary wave trains, in some cases chased over many kilometers from generation to dissipation stages. The acoustic system was deployed in both down-looking and side-looking mode, allowing scattering anisotropy during the passage of internal solitary waves to be investigated. In addition, 5 depth-resolved net tows (MOCNESS) were performed during this experiment in order to quantify biological scatterers.

Analysis of microstructure and biological measurements: Jim Moum is primarily responsible for the analysis of the microstructure measurements, and much of the data collected during the field experiment has been analyzed. These data have been used with existing scattering models (Lavery *et al.*, 2003) to

predict scattering from microstructure, and to assess the importance of salinity versus temperature microstructure. These data helped guide the locations for which intensive acoustic analysis was performed. The shelf-break MOCNESS tows (2-5) have been analyzed for composition, size, and abundance of zooplankton. Predictions of scattering from zooplankton based on existing scattering models (Lavery et al., 2007) have been performed for these tows (the “forward problem”) to determine the contribution to scattering from biology and to determine the dominant biological scatterers.

Analysis of acoustic scattering data: The analysis of the broadband acoustic scattering data has focused on locations at which particularly strong temperature gradients and high dissipation rates were observed, such as Kelvin-Helmholtz shear instabilities (Moum *et al.*, 2003). Elevated scattering from microstructure relative to zooplankton is expected at these locations. Two manuscripts have resulted from this recent work (one submitted, one in press).

Turbulence anisotropy: Doris Leong, a recently graduated M.Sc. student at Dalhousie University has used the broadband acoustic scattering spectra measured during the SW06/NLIWI experiment to assess the importance of turbulence anisotropy (Leong, 2009). A manuscript will be submitted to the J. Acoustic. Soc. Am.

RESULTS

High-resolution imaging of small-scale physical processes: Broadband acoustic scattering measurements enable the use pulse compression signal processing techniques to obtain very high resolution images of many nonlinear internal waves. In combination with the high ping rate (1 Hz), these techniques have allowed fine scale physical processes, such as Kelvin-Helmholtz shear instabilities (Fig. 1), typically not well resolved by the direct microstructure measurements, to be imaged at very high resolution. Though the direct microstructure measurements provide very high resolution measurements in the vertical, the profiles are relatively sparse (one profile every 2-4 minutes) relative to the acoustic measurements or the spatial scales of the KH instabilities.

Analysis of biological samples and the forward problem based on these data: All the MOCNESS tows performed on the continental shelf during the SW06 experiment have been analyzed (MOCs 2-5). The results show that, in general, biomass and numerical abundance of zooplankton are dominated by copepods, with larger copepods located in a deep scattering layer and the shallower waters being populated by smaller copepods. All tows were performed during day light hours. Scattering predictions based on these data and available zooplankton models (Lavery et al., 2007) have shown that the predicted scattering from zooplankton is dominated by copepods, amphipods, and pteropods, depending on the frequency, depth, and location.

Forward problem based on microstructure data: Scattering predictions have also been made based on the microstructure data and turbulent microstructure scattering models, at select locations. These predictions suggest that the scattering from microstructure is dominated by temperature and not salinity microstructure, as would be expected based on the temperature and salinity gradients.

Scattering due to small-scale physical processes versus biology: Though the frequency response of the scattering was often consistent with scattering from small zooplankton (scattering increasing with increasing frequency: Fig. 2), some regions have been found in which the scattered frequency spectra

are indicative of scattering from physical processes (Fig. 2). Specifically, scattering spectra from Kelvin-Helmholtz shear instabilities were frequently consistent with scattering from microstructure alone (scattering decreases with increasing frequency: Fig. 3).

Inversion of broadband data for biological and physical parameters: Simple least squares inversions of the broadband scattering data have been performed at locations in which the scattering spectra are consistent with scattering from small zooplankton alone, and consistent with scattering from microstructure alone. These inversions rely heavily on existing scattering models. For zooplankton, a single scattering type is assumed and the inversions result in size and abundance of that type of scatterer. For microstructure, the inversions allow the dissipation rate of turbulent kinetic energy (Fig. 4) and temperature variance (Fig. 5) to be deduced. For both these types of inversions the results are consistent with the direct sampling techniques, though high noise levels on the two highest frequency channels only allowed high values of dissipation rates of turbulent kinetic energy to be inferred.

Scattering anisotropy: By comparing broadband acoustic scattering spectra measured in horizontal and vertical mode, it has been possible to assess the importance of anisotropy on scattering. The overall scattering shows statistical patterns in spectral shape that suggests anisotropy occurs in either the biology or microstructure, though there was insufficient bandwidth and/or groundtruthing to determine which. However, turbulence dissipation rates inferred from acoustic inversions of spectra yield no clear evidence of small-scale turbulence anisotropy.

IMPACT/APPLICATIONS

It is important to understand the circumstance under which different processes and/or targets contribute to high-frequency acoustic scattering. For example, a common misconception is that high-frequency acoustic scattering in the water-column is dominated by biological organisms. Only recently has it become more accepted that microstructure can also contribute to scattering, under certain circumstances. The results of the measurements performed here provide additional evidence that small-scale physical process can be significant contributors to volume scattering in regions of internal solitary waves. This project has also developed high-frequency broadband acoustic scattering techniques that 1) increase the circumstances under which scattering from microstructure and biology can be distinguished, and 2) increase the spatial resolution with which physical and biological processes are imaged, which is especially relevant as it has become increasingly evident that thin biological and physical layers are prevalent in coastal regions.

RELATED PROJECTS

- “Remote Sensing of Temperature and Salinity Microstructure in Rivers and Estuaries Using Broadband Acoustic Scattering Techniques,” Lavery, A.C., Terray, E., and Gallager, Scott. Funded by ONR Physical Oceanography.
- “Development of an autonomous broadband acoustic scattering system for remote characterization of zooplankton,” Lavery, A.C., Terray, E., and Sutor, M. Funded by ONR Marine Mammals and Biology.

FIGURES

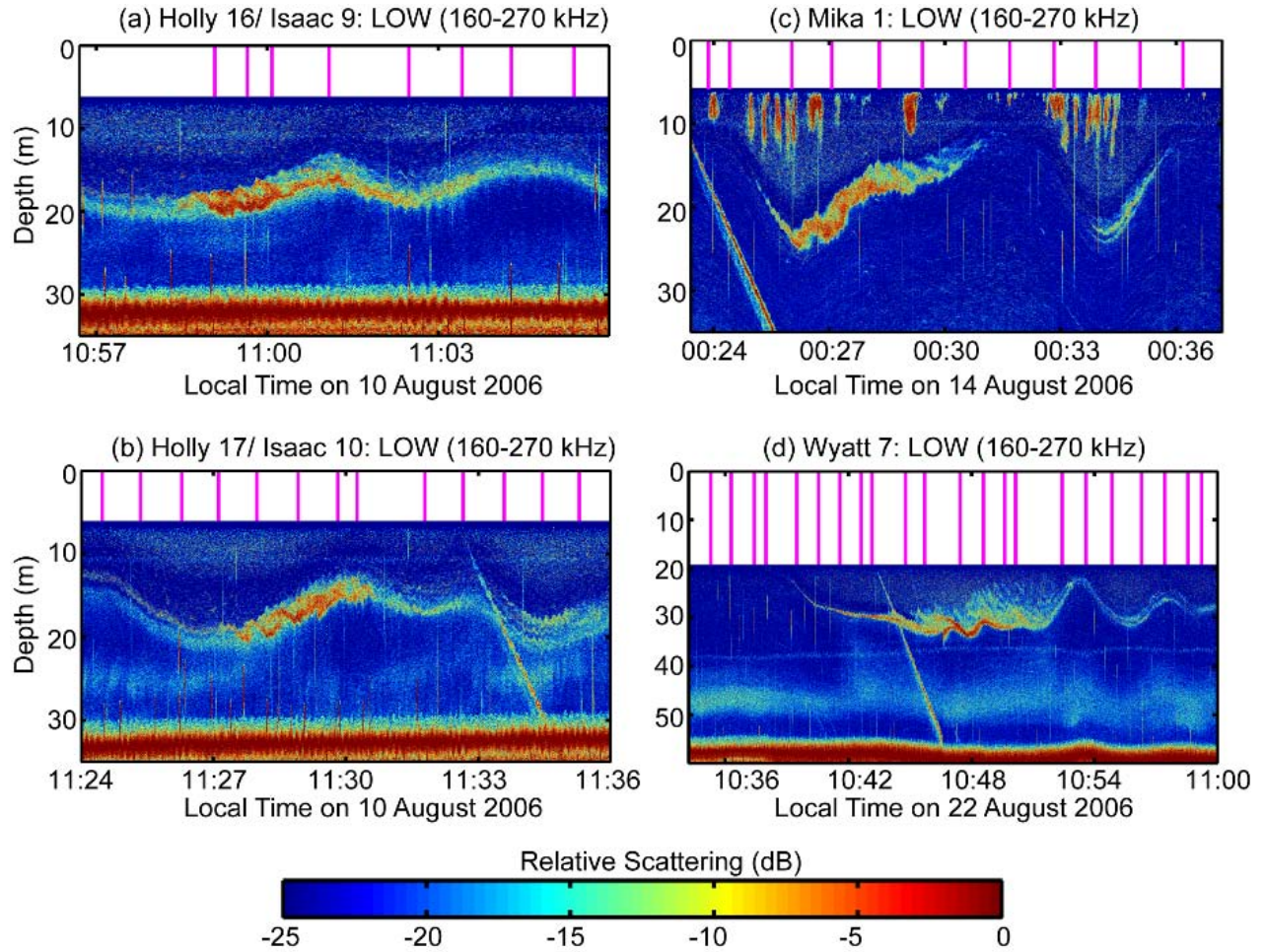


Figure 1: Compressed pulse output for the LOW (160-270 kHz) frequency channel during the passage of four non-linear internal waves illustrating high-resolution images of scattering from Kelvin-Helmholtz shear instabilities. The vertical lines at the top of each panel denote the times of the direct microstructure profiles. All images in this report have the same color bar scale.

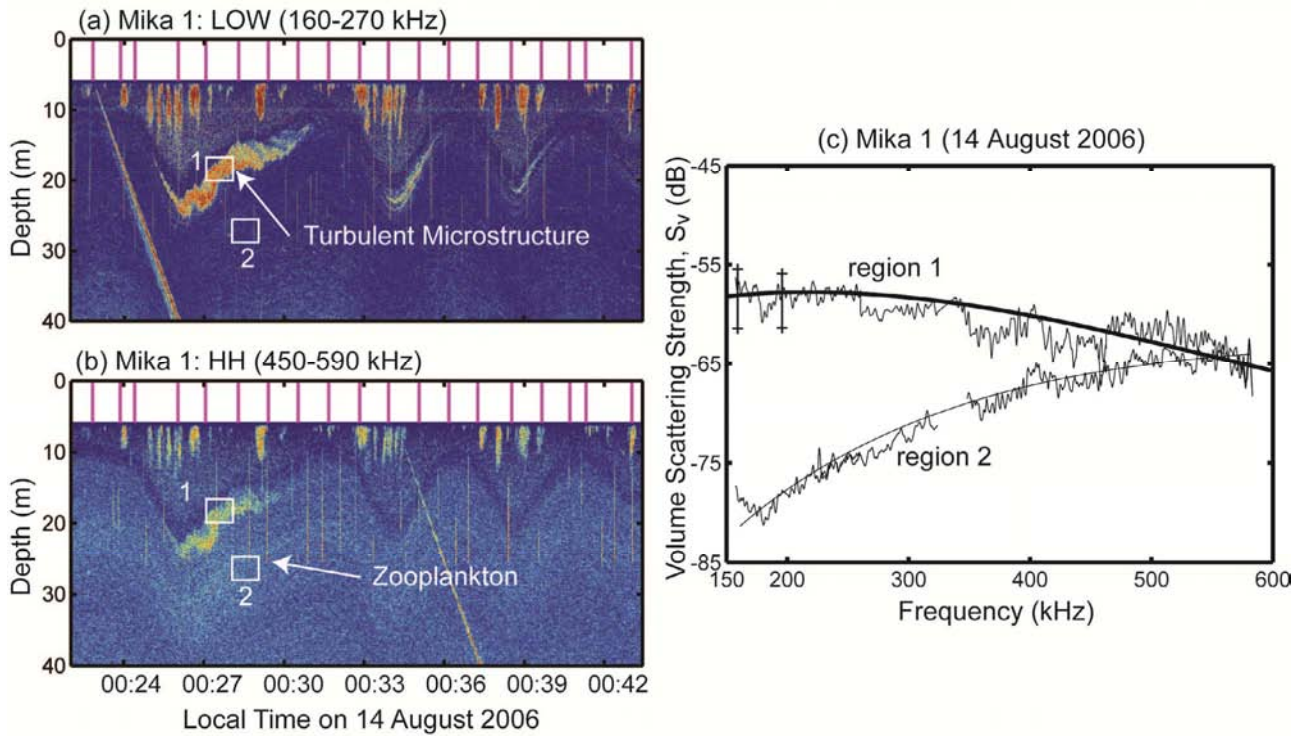


Figure 2: Compressed pulse output for the (a) LOW (160-270 kHz) and (b) HH (450-590 kHz) frequency channels during the passage of nonlinear internal wave Mika. The scattering spectra (c) associated to the KH shear instability (region 1) are generally consistent with scattering from microstructure, while the spectra associated to the deeper more diffuse scattering layer (region 2) are consistent with scattering from small zooplankton.

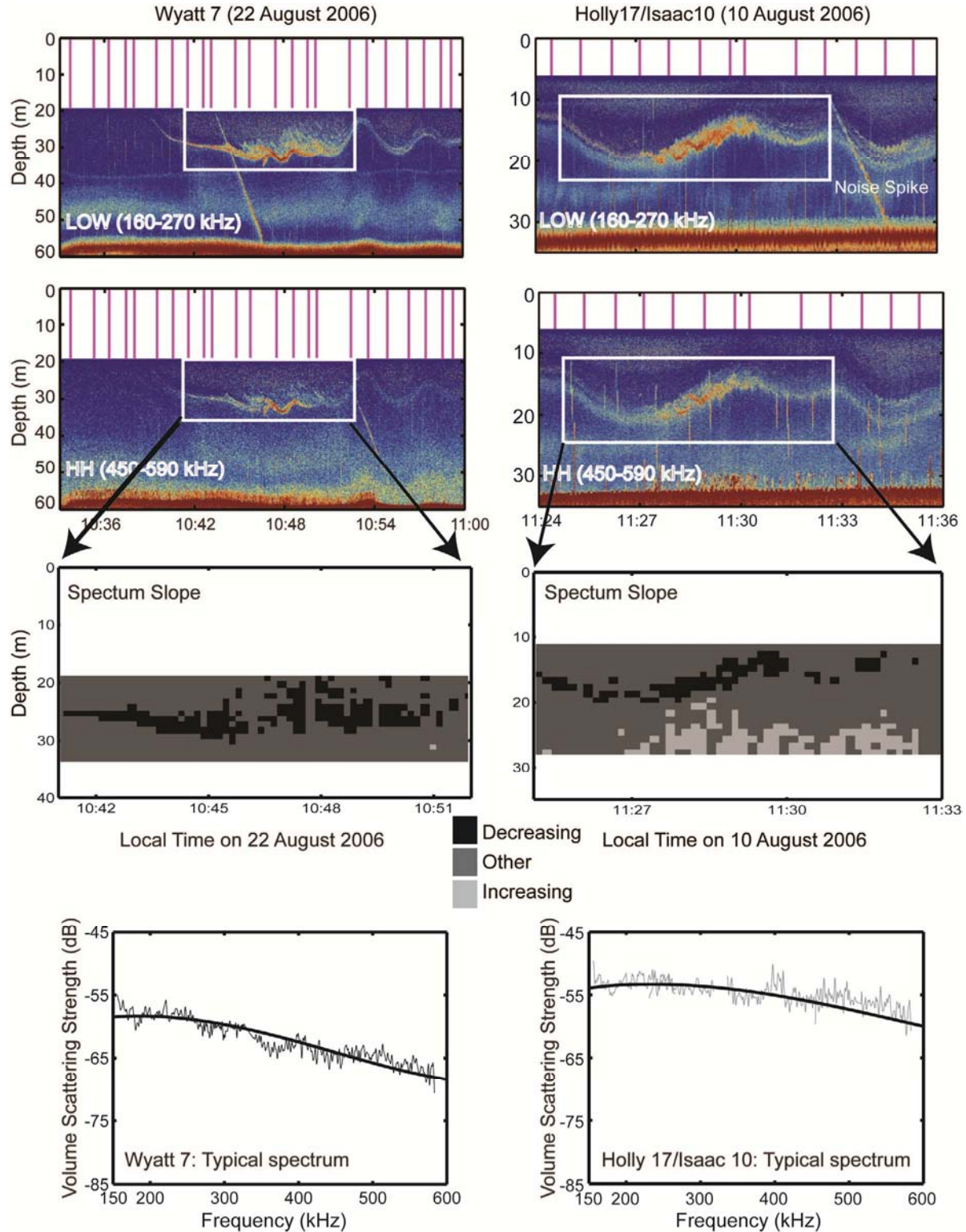


Figure 3: Left hand panels: Internal wave Wyatt 7. Right hand panels: Internal wave Holly17/Isaac 10. Top panels: Compressed pulse output for the LOW (160-270 kHz) frequency channel. Second row: Compressed pulse output for the HH (450-590 kHz) frequency channel. Third row: Slope analysis for the measured spectra. Final row: Typical spectra associated to the KH shear instabilities.

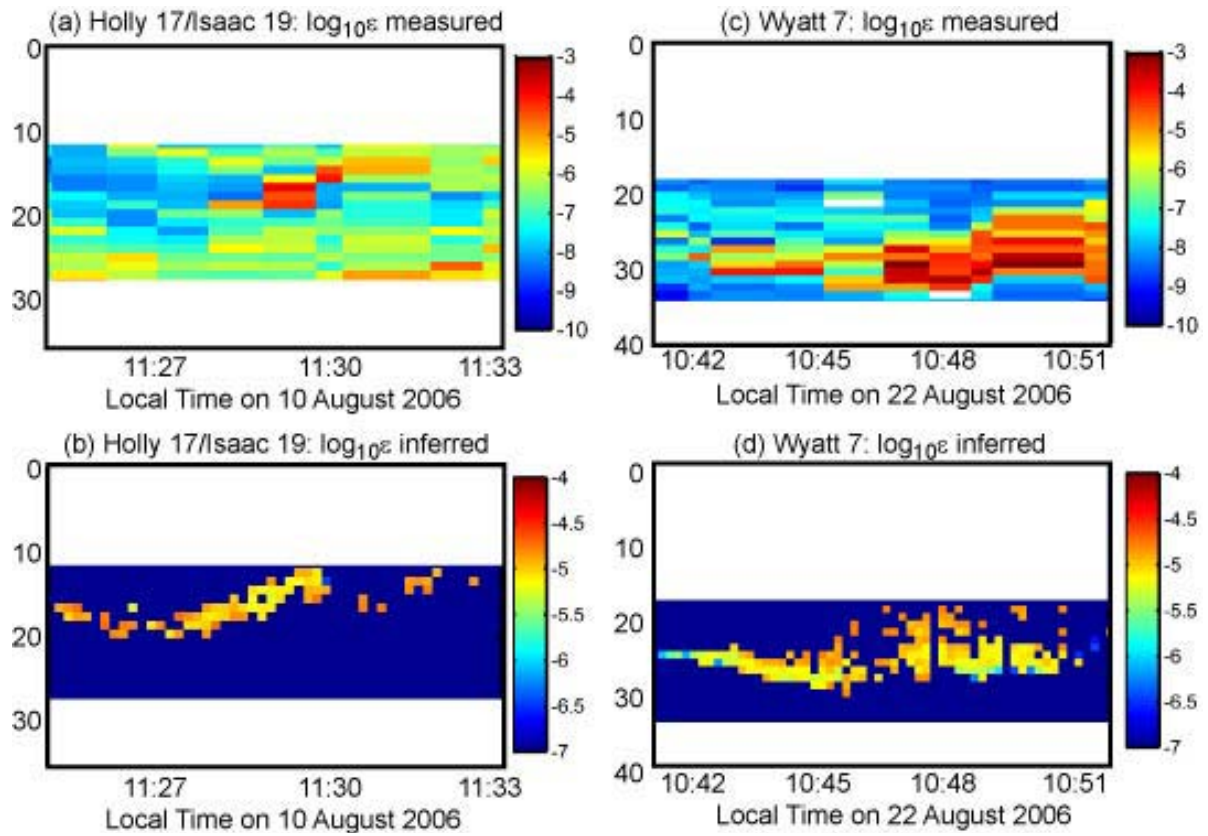


Figure 4: Comparison of the directly measured and acoustically inferred dissipation rates of turbulent kinetic energy for nonlinear internal wave Holly 17/Isaac 10 (a and b), and for nonlinear internal wave Wyatt 7 (c and d).

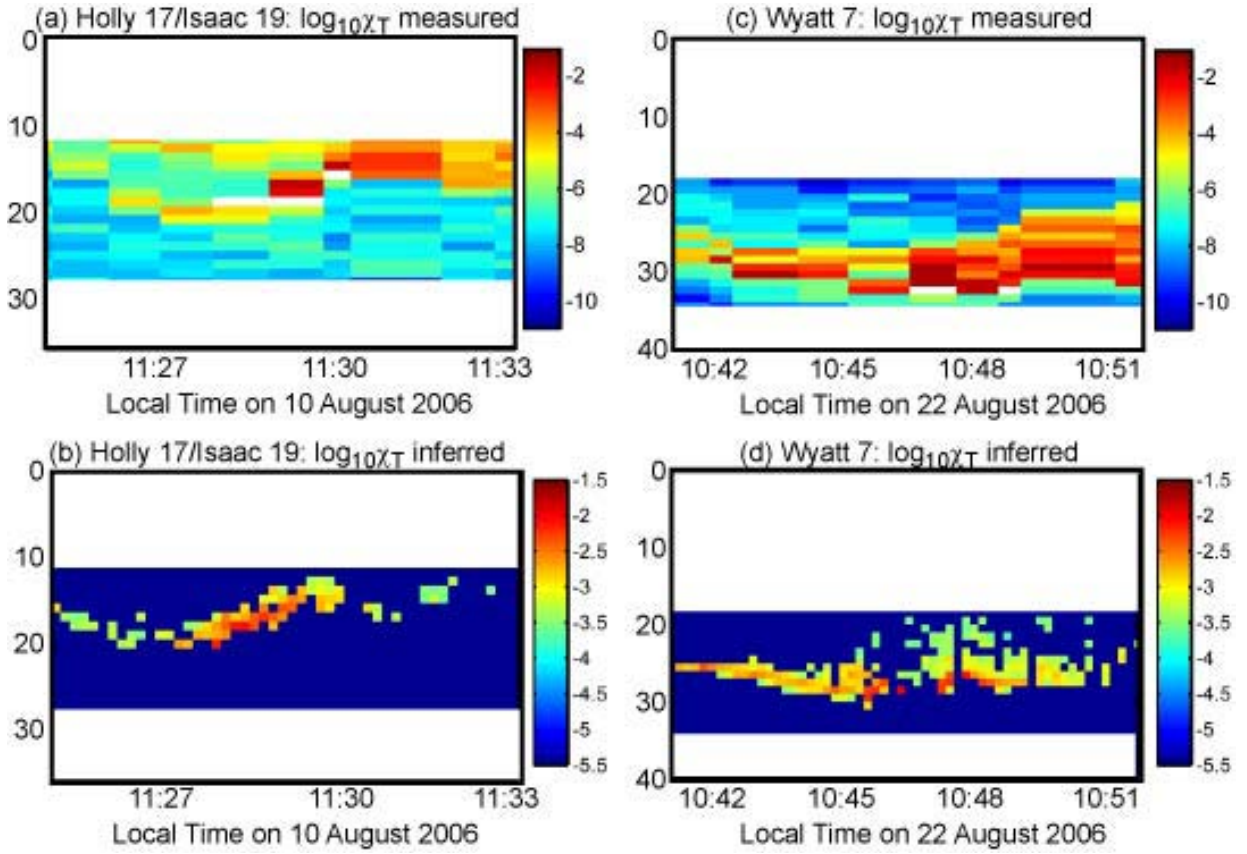


Figure 5: Comparison of the directly measured and acoustically inferred dissipation rates of temperature variance for nonlinear internal wave Holly 17/Isaac 10 (a and b), and for nonlinear internal wave Wyatt 7 (c and d).

REFERENCES

- Au, W.W.L. and Benoit-Bird, K.J. (2008). "Broadband backscatter from individual Hawaiian mesopelagic boundary community animals with implications for spinner dolphin foraging," *The Journal of the Acoustical Society of America* 123: 2884-2894.
- Au, W.W.L., Branstetter, B. K., Benoit-Bird, K.J., and Kastelain, R. A. (2009). "Acoustic basis for fish basis discrimination by echolocating dolphins and porpoises," *The Journal of the Acoustical Society of America* 126: 460-467.
- Chu, D., and Stanton, T. K. (1998). "Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton," *J. Acoust. Soc. Am.* 104(1), 3955.
- Foote, K. G., Atkins, P.R., Francis, D.T.I., and Knutsen, T. (2005). "Measuring echo spectra of marine organisms over a wide bandwidth," *Proceedings of the International Conference on Underwater Acoustic Measurements: Technologies and Results*, edited by J.S. Papadakis, and L. Bjørnø, Heraklion, Greece, 28 June - 1 July 2005, pp. 501-508.
- Goodman, L. (1990). "Acoustic scattering from ocean microstructure," *Journal of Geophysical Research* 95(C7): 11557-11573.
- Goodman, L. and Oeschger, J. (2003). "Acoustic scattering from a thermally driven buoyant plume revisited," *The Journal of the Acoustical Society of America* 113: 1353-1367.
- Holliday, D.V. (1972). "Resonance structure in echoes from schooled pelagic fish," *Journal of the Acoustical Society of America* 51(4): 1322-1332.
- Lavery, A. C., Schmitt, R. W., and Stanton, T. K. (2003). "High-frequency acoustic scattering from turbulent oceanic microstructure: the importance of density fluctuations," *J. Acoust. Soc. Am.* 114(5), 2685-2697.
- Lavery, A.C., and Ross, T. (2007) "Acoustic scattering from double-diffusive microstructure," *J. Acoust. Soc. Am.* 122(3), 1449-1462.
- Lavery, A. C., Wiebe, P. H., Stanton, T.K., Lawson, G.L., Benfield, M.C., and Copley, N. (2007). "Determining dominant scatterers of sound in mixed zooplankton populations," *J. Acoust. Soc. Am.* 122(6), 3304-3326.
- Lee, W.-J., Stanton, T.K., and Lavery, A.C. (2009). "Broadband acoustic backscattering from live squid: Experiment and analysis," *The Journal of the Acoustical Society of America*, 125: 2550.
- Love, R. H., Fisher, R. A., Wilson, M. A., and Nero, R.W. (2004). "Unusual swimbladder behavior of fish in the Cariaco Trench," *Deep-Sea Research I* 51(1): 1-16.
- Lundgren B., and Nielsen, J.R., (2008). "A method for the possible species discrimination of juvenile gadoids by broad-bandwidth backscattering spectra vs. angle of incidence," *ICES Journal of Marine Science* 65: 581-593.
- Moum, J.N., M.C. Gregg, R.C. Lien and M.E. Carr, (1995). "Comparison of turbulence kinetic energy dissipation rate estimates from two ocean microstructure profilers," *Journal of Oceanic and Atmospheric Technology* 12: 346-366.
- Moum, J.N., Farmer, D. M., Smyth, W. D., Armi, L., Vagle, S. (2003). "Structure and generation of turbulence at interfaces strained by internal solitary waves propagating shoreward over the continental shelf," *J. Phys. Oceanogr.* 33, 2093-2112.
- Nero, R.W., Thompson, C.H., and Love, R.H. (1998). "Low-frequency acoustic measurements of Pacific hake, *Merluccius productus*, off the west coast of the United States," *Fishery Bulletin* 96(2): 329-343.

- Nicol, S. and Endo, Y. (1999). "Krill fisheries: Development, management and ecosystem implications," *Aquatic and Living Resources* 12(2): 105-120.
- Reeder, D.B., Jech, J.M., and Stanton, T.K. (2004). "Broadband acoustic backscatter and high resolution morphology of fish: Measurement and modeling," *The Journal of the Acoustical Society of America* 116: 747-761.
- Roberts, P. L. D. and Jaffe, J. S. (2008). "Classification of live, untethered zooplankton from observations of multiple-angle acoustic scatter," *The Journal of the Acoustical Society of America* 124: 796-802.
- Ross, T. and Lueck, R. (2003). "Sound scattering from oceanic turbulence," *Geophysical Research Letters* 30.
- Ross, T. and Lawson, G. (2009). "Long-term broadband acoustic observations of zooplankton scattering layers in Saanich Inlet, British Columbia," *The Journal of the Acoustical Society of America* 125: 2551.
- Seim, H. E., Gregg, M. C., and Miyamoto, R. T. (1995). "Acoustic backscatter from turbulent microstructure," *Journal of Oceanic and Atmospheric Technology* 12(2): 367-380.
- Simmonds, J. and MacLennan, D. (2005). *Fisheries Acoustics*, 2nd ed., Blackwell Publishing.
- Simmonds, E. J. and Armstrong, F. (1990). "A wide band echosounder: Measurement on cod, saithe, herring and mackerel from 27 to 54 kHz," *ICES/FAO Int. Symp. Fish. Acou.*, Seattle Washington USA. *Rapp. P.-v. Reun. Cons. perm. int. Explor. Mer.* 189: 381-387.
- Simmonds E.J., Armstrong, F., and Copland P.J. (1996). "Species identification using wide band backscatter with neural network and discriminant analysis," *ICES J. Marine Science* 53: 189-195.
- Stanton, T. K., and Chu, D. (2008). "Calibration of broadband active acoustic systems using a single standard spherical target," *Journal of the Acoustical Society of America* 124: 128-136.
- Stanton, T. K., Chu, D., and Jech, M. Resonance classification and high resolution imagery of swimbladder-bearing fish using a broadband echosounder. *ICES Journal of Marine Science*: accepted.
- Thompson, C.H. and Love, R. H. (1996). "Determination of fish size distributions and areal densities using broadband low-frequency measurements," *ICES J. Marine Science* 53(2): 197-201.
- Warren, J.D., Stanton, T.K., Wiebe, P.H., and Seim, H.E. (2003). "Inference of biological and physical parameters in an internal wave using multiple-frequency, acoustic-scattering data," *ICES Journal of Marine Science* 60(5): 1033-1046.
- Zakharia, M. E., Magand, F., Hetroit, F., and Diner, N. (1996). "Wideband sounder for fish species identification at sea," *ICES Journal of Marine Science* 53: 203-208.

PUBLICATIONS

- Lavery, A.C., Chu, D., and Moum, J., "Measurements of acoustic scattering from zooplankton and oceanic microstructure using a broadband echosounder," *ICES J. Marine Science* [in press, refereed].
- Ross, T., and Lavery, A.C., "Acoustic detection of oceanic double-diffusive convection: A feasibility study," *J. Atmos. Ocean. Tech.* [submitted, refereed].

Leong, D. "Assessing the isotropy of ocean turbulence using broadband acoustics," M.Sc. Thesis, Dalhousie University, Canada, 2009.

STUDENTS ASSOCIATED TO THIS PROJECT

Doris Leong, Graduate Student, Dalhousie University, Canada. July 2006- present.

Paul Heslinga, WHOI Guest Summer Student, Cruise Participation. July-August 2006.

HONORS/AWARDS/PRIZES

Andone C. Lavery was awarded a WHOI Coastal Ocean Institute Fellowship from 2006-2009.